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AN EXTENSION TO THE USGS SHAKECAST FOR SYSTEM-LEVEL IMPACT ASSESSMENT USING A BAYESIAN APPROACH

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Abstract. The United States Geological Survey (USGS) ShakeCast provides near-real-time post-earthquake impact and inspection metrics for critical infrastructure facilities following an event. The system sends automatic notifications with information on inspection priorities based on damage estimates using a suite of fragility models and ShakeMap ground motion parameters. The current system provides only asset-level damage estimates, which can be further used for system-level impact assessment through a Bayesian approach. This paper describes a methodology for an application of a Bayesian approach using the product of the ShakeCast and demonstrates an example of its application for the road bridge network located in the Wheatbelt Region of southwestern Western Australia, inland from Perth. This region has been the subject of detailed collaborative research on infrastructure assets that has led to an operational piloting of ShakeCast in Geoscience Australia's National Earthquake Alerts Centre. The bridge network in this research consists of approximately 100 bridges with earthquake vulnerability attributed. The performance of the selected routes is assessed assuming the bridges are the only vulnerable elements in the road network that can fail due to ground shaking. This proposed extension to ShakeCast will enable road transport asset managers to assess the likelihood of system operational status near-real-time following an event.

1 INTRODUCTION

The United States Geological Survey (USGS) ShakeCast is an openly available near-real-time post-earthquake information management system developed by USGS [1]. The outputs from this system have been widely used by public and private emergency services, infrastructure operators, and facility engineers [2]. The system sends automatic notification with the information on inspection priorities based on damage estimates using fragility models and ShakeMap [3] ground motion parameters after an event.

The current system provides asset-level inspection priorities based on asset-level damage estimates. These can be further used for system-level impact assessment once the system reliability is modelled based on the reliability of individual components and how they interact.

This paper describes an application of a Bayesian approach using the product of ShakeCast and demonstrates an example of its application for the road bridge network located in the Wheatbelt Region of southwestern Western Australia, inland from Perth. Two cases were considered for demonstration: 1) preferred paths were chosen before the event, 2) viable paths were identified after the event. For both cases, Bayesian inferences were carried out to compute the following probabilities: 1) the probability of a path functioning after the event, 2) the probability of system failure, and 3) the conditional probability of a bridge failure given system failure.

2 USGS SHAKECAST

The goal of the ShakeCast system is to provide near-real-time damage and inspection metrics to facilitate users' inspection priorities and protocols [1]. Damage probabilities are computed for each facility using ShakeMap intensity, and inspection priorities are compiled in descending order of the damage probability. For instance, Figure 1 shows the summary report for the bridges located in the Wheatbelt Region of southwestern WA, inland from Perth after the event of M_L 4.0 near Wyalkatchem, WA occurred on 27 March 2025 (https://earthquakes.ga.gov.au/event/ga2025gagmzg). This region has been the subject of detailed collaborative research on infrastructure assets that has led to an operational piloting of ShakeCast in Geoscience Australia's National Earthquake Alerts Centre [4]. Table 1 is an excerpt from the report, where asset-level shaking intensity and probabilities of damages are set out. Note that gray, green, yellow, orange, and red correspond to None, Slight, Moderate, Extensive, Complete damage state, respectively, and the damage probabilities are expressed in percent. Given the low ground motion intensity of this event, damage to bridge asset was not expected, nor subsequently reported from field inspection.

ShakeCast Report

ga2025gagmzg - MLa 4.0 - Wyalkatchem, WA - v1

Assessed Inspection Priority Category

Total Facilities Evaluated: 213
High: 0
Medium-High: 0
Medium: 0
Low: 0
None: 213

Disclaimer

The assessment of ground shaking severity and resulting bridge damage is approximate with much associated uncertainty in the process. The damage probability assessed is based on fragility functions published in the HAZUS technical manual (see link below) for classes of bridge structures found in the US that have been mapped to Western Australian bridges using available bridge asset information. For these reasons the attribution of inspection priority should be taken as an indication of which assets have been damaged and that the actual damage will be subsequently assessed through physical inspection on site. No responsibility is taken for the accuracy of the information provided.

HAZUS Technical Manual:
https://www.fema.gov/sites/default/files/documents/fema_hazus-earthquake-model-technical-manual-5-1.pdf

Figure 1: ShakeCast report for the bridges after the event of ML 4.0 near Wyalkatchem, WA.

Table 1: Asset-level damage report, an excerpt from the ShakeCast report for the bridges after the event of M_L 4.0 near Wyalkatchem, WA. PSA10 represents the pseudo-spectral acceleration at 1.0 sec.

Name	Alert level	Distance (km)	Gray	Green	Yellow	Orange	Red	PGA (g)	MMI	PSA10 (g)
277	Gray	100.38	100	0	0	0	0	0.04	1.4	0.01
278	Gray	101.38	100	0	0	0	0	0.06	1.7	0.02
279	Gray	101.71	100	0	0	0	0	0.03	1.2	0.01

3 BAYESIAN NETWORK

An infrastructure network can be modelled as a system of components connected in either parallel or series or as a combination of both. As system performance is conditioned on the state of each component, the network can be modelled as a Bayesian network, which is a probabilistic graphical model representing a set of variables and their conditional dependencies through a directed acyclic graph (DAG). For instance, a road network can be modelled as a system consisting of bridges as components, as depicted in Figure 2, assuming the bridges are the only vulnerable elements in the road network that can fail due to ground shaking.

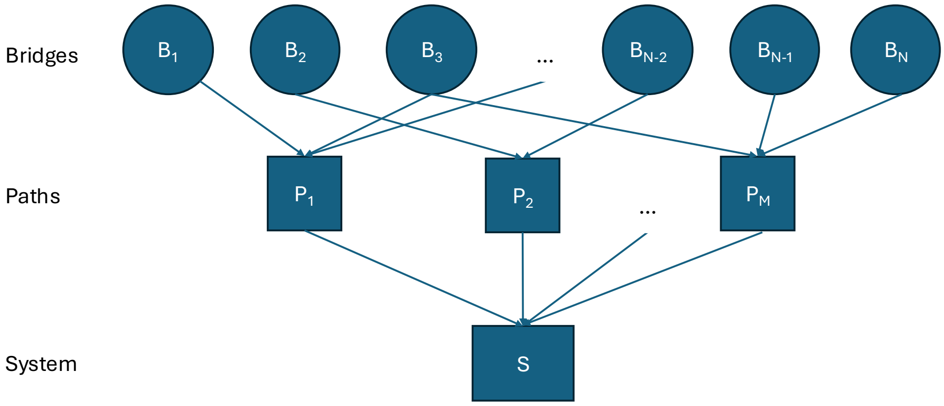

Figure 2: Bayesian network diagram for a road network consisting of N bridges and M paths.

In a Bayesian network, the joint distribution of the random variables can be formulated as the product of the conditional distribution given the parent nodes:

$$P(S, P_1, \dots, P_M, B_1, \dots, B_N) = P(S|P_1, \dots, P_M) \times \prod_{i=1}^{M} P(P_i|B_1, \dots, B_N) \times \prod_{j=1}^{N} P(B_j) \quad (1)$$

In this study, Bayesian network was constructed using a python toolkit MBNpy (https://github.com/jieunbyun/MBNpy), which is a Python implementation of the algorithm of matrix-based Bayesian network using the conditional probability matrices [5]. Two cases were considered: 1) preferred paths were chosen before the event, 2) viable paths were identified after the event. For both cases, Bayesian inferences were carried out to compute the following probabilities: 1) survivability, the probability of a path functioning after the event, $P(P_i = 1)$, 2) the probability of system failure, $P(S = 0)$, and 3) the conditional probability of a bridge failure given system failure, $P(B_i = 0|S = 0)$. For the first case in which preferred paths were chosen before the event, these probabilities were estimated deterministically, while lower and upper bounds of the probabilities were estimated for the second case due to the incompleteness of the identified survival and failure rules (owing to the large number of bridges) under the branch and bound for reliability analysis of general coherent systems (BRC) algorithm [6].

The survivability, $P(P_i = 1)$ was estimated by summing $P(S, P_1, \dots, P_M, B_1, \dots, B_N)$ over all variables except P_i. Similarly, the probability of system failure, $P(S = 0)$ was computed by summing $P(S, P_1, \dots, P_M, B_1, \dots, B_N)$ over all variables except S. The conditional probability of a bridge failure given system failure, $P(B_i = 0|S = 0)$ was computed:

$$P(B_i = 0|S = 0) = \frac{P(B_i=0,\ S=0)}{P(S=0)} = \frac{P(S=0|B_i=0) \times P(B_i=0)}{P(S=0)} \tag{2}$$

The lower and upper bounds of the probability of system failure were estimated $\bar{P}(S = 0)$ and $1 - \bar{P}(S = 1)$, respectively. $\bar{P}(\cdot)$ denotes the probability obtained from incomplete identification of rules by BRC [6]. The lower and upper bounds of the conditional probability were estimated $\frac{\bar{P}(B_i=0,S=0)}{\bar{P}(S=0)}$ and $\frac{1-\bar{P}(B_i=1,S=0)-\bar{P}(B_i=1,S=1)-\bar{P}(B_i=0,S=1)}{1-\bar{P}(S=1)}$, respectively.

4 BAYESIAN INFERENCE FOR BRIDGE NETWORK IN WHEATBELT REGION

Bayesian inference was applied to the road bridge network located in the Wheatbelt Region of southwestern WA, inland from Perth. The road network connecting 6 regional towns consists of approximately 100 bridges spatially distributed in Figure 3. Each bridge was assigned a HAZUS bridge vulnerability class [7] based on structural characteristics which included the level of seismic design and number of spans.

The first case assumed that preferred paths connecting two regional towns were chosen before the event. For the trip from Wooroloo, WA to Merredin, WA, three paths were chosen as depicted in Figure 3. Path 1 and 2 have a substantial section in common from Wooroloo to Merredin, while Path 3 goes through York instead of Northam.

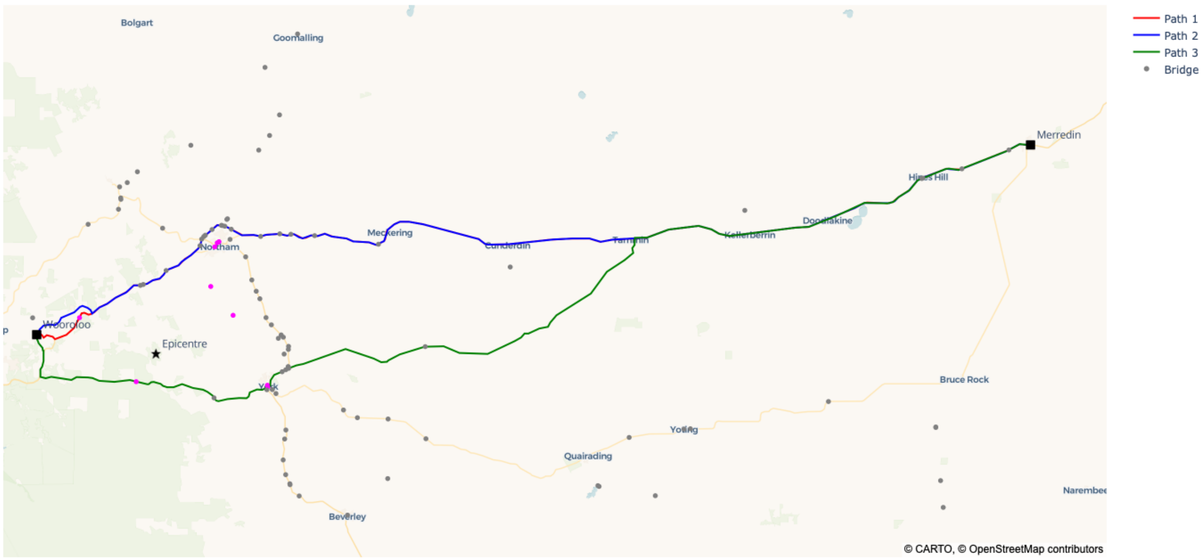

Figure 3: Map of the road bridge network located in the Wheatbelt Region of southwestern WA.

For the scenario, a ground motion field was generated using the OpenQuake v3.20 [8] for M_w 6.58 event located approximately 20km from Northam, WA. Damage probabilities of four damage states were computed using the fragility functions associated with the HAZUS bridge class, which are implemented in the ShakeCast. It was assumed that bridge function failed if it sustained extensive or worse damage. Only three bridges of the selected three paths were computed to have the failure probability larger than 0.1 given the scenario, as marked in pink dots in Figure 3.

Firstly, survivability, the probability of a path functioning after the event was computed and summarised in Table 2. The probability of system failure was computed to be 10.5% in which all paths would have unusable bridges. Optimal path decision can be informed by the combination of travel time and survivability. Secondly, the conditional probability of a bridge failure given system failure was computed and presented in Figure 4. This can be used, along with the ShakeCast assessment of probable bridge damage state, in prioritising recovery work across the bridges. Asset manager would have both an assessment of bridge damage and the likelihood that this outcome has impacted the connectivity of the transport system.

Table 2: Probability of path functioning after the event for the pre-selected paths.

Path	1	2	3
Travel time (mins)	136.4	136.6	141.4
Survivability (%)	59.8	77.1	54.1

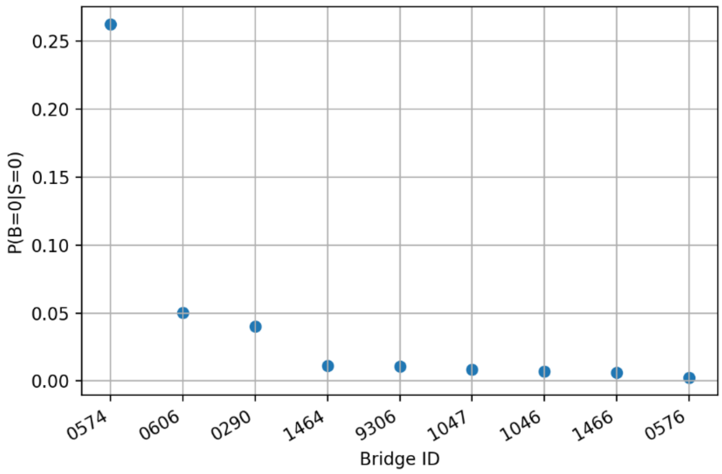

Figure 4: Probability of bridge failure given system failure for the first case.

In the second case, a path was assumed to be disconnected if the travel time was longer than the threshold time, which was set to be 1.5 hours addition to the shortest travel time before the event. In this example, the maximum number of rules was set to be 20, which resulted in 8 connected paths and 12 disconnected paths under the BRC algorithm. The shortest 5 paths are set out in Table 3 along with corresponding travel time and survivability. Note that the path number in the table was assigned by the order of travel time, which does not match to the number in the first case. The lower and upper bounds of the system failure were estimated to be 0.1% and 0.2%, respectively. The lower and upper bounds of the conditional probability of a bridge failure given system failure were computed and presented in Figure 5.

Another simulation was carried out to illustrate limited path availability due to vehicle weight. For this each road section was assigned a vehicle weight limit along with road bridges on the section based on road type. Three values of the vehicle weight limit (50t, 75t and 100t) were assigned and paths were searched assuming a 75t vehicle could only pass along a section having a capacity equal to or larger than the vehicle weight. The simulation resulted in 4 connected paths and 16 disconnected paths, and lower and upper bounds of the system failure estimated to be 8.5% and 10.2%, respectively. As expected, considering the vehicle weight limit resulted in higher system failure and a smaller number of viable paths. The available 4 paths are set out in Table 3 along with corresponding travel time and survivability. The lower and upper bounds of the conditional probability of a bridge failure given system failure were computed and presented in Figure 5.

Table 3: Probability of path functioning after the event for the second case.

Vehicle weight limit	Path	1	2	3	4	5
Not considered	Travel time (mins)	136.6	140.3	141.4	149.0	154.3
	Survivability (%)	77.1	72.3	54.1	49.8	54.4
Considered	Travel time (mins)	136.6	146.7	166.2	183.7	
	Survivability (%)	77.1	66.6	41.2	15.6	

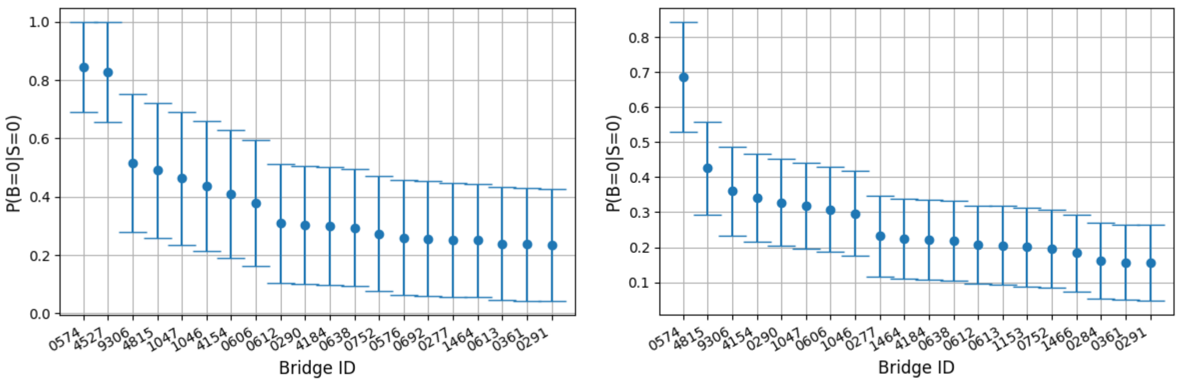

Figure 5: Probability of bridge failure given system failure for the second case: a) vehicle weight limit not considered, b) vehicle weight limit considered.

4 CONCLUSIONS

In this research, a Bayesian approach was applied to extend the functionality of the USGS ShakeCast, by enabling the system-level impact to be assessed in addition to asset-level damage estimates. Through the example of the road bridge network located in the Wheatbelt Region of southwestern WA, feasibility of the extended functionality was demonstrated. The reported work has focused on a single event. The potential of this Bayesian approach will be further explored outside of an operational approach to examine how the Bayesian outcomes of a stochastic event set of earthquake impacts can provide information for prioritising bridge asset mitigation/replacement.

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